International Journal of Thermal Technologies
ISSN 2277 - 4114

Research Article

Numerical Analysis of a Helical Coiled Heat Exchanger using CFD

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Accepted 02 November 2013, Available online 01 December 2013, **Vol.3, No.4 (Dec 2013)**

Abstract

Heat exchangers are the important equipments with a variety of industrial applications including power plants, chemical, refrigeration and air conditioning industries. Helically coiled heat exchangers are used in order to obtain a large heat transfer area per unit volume and to enhance the heat transfer coefficient on the inside surface. This paper deals with the CFD simulation of helical coiled tubular heat exchanger used for cooling water under constant wall temperature conditions. The results are validated by the results obtained by the numerical correlations used by different researchers. CFD results are also compared with the results obtained by the simulation of straight tubular heat exchanger of the same length under identical operating conditions. Results indicated that helical heat exchangers showed 11% increase in the heat transfer rate over the straight tube. Simulation results also showed 10% increase in nusselt number for the helical coils whereas pressure drop in case of helical coils is higher when compared to the straight tube.

Keywords: *Helical Coiled Heat Exchanger, CFD*

Introduction

Flow through a helical coiled tube has observed wide applications including power plants, refrigeration and air conditioning equipment, chemical and food processing industries. Fluid flowing through a coiled tube will experience a centrifugal force. As a result of this it induces a secondary flow in the tubes. This secondary flow in the tubes has significant ability to enhance the heat transfer. Because of the secondary flow consisting of two vortices perpendicular to the axial flow direction the heat transfer will occur not only by diffusion in the radial direction but also by convection. Contributions of this secondary convective transport dominate throughout the overall process and enhance the rate of heat transfer per unit length of the tube compared to a straight tube of equal length.

The first approximation of steady motion of incompressible fluid flowing through a coiled tube was investigated by (Dean W.R, 1927). It was observed that reduction in the rate of flow due to the curvature depends on the variable k = $2\,\frac{Re^2\,r}{R}$ for low velocities and small values of $\frac{r}{R}$. He concluded that the flow in curved pipes is more stable than flow in a straight pipe. (Devarahalli, et al, 2004) carried out an experimental investigation of the natural convective heat transfer from helical coiled tubes in water. A model was developed to predict outlet temperatures and nusselt number based on the inlet conditions. The results of predicted temperatures and nusselt numbers were very close to the experimental values. (Fakoor, et.al, 2013) studied the pressure drop characteristics of nano fluid flow inside a vertical helical coiled tube for laminar flow conditions. Experiments were conducted by varying the pitch circle diameters and also the tube diameters. Results indicated that using helical tubes instead of straight tubes increases the pressure drop exponentially. (Pramod Purandare, et al, 2012) carried out a comparative analysis of the different correlations given by different researchers for helical coil heat exchanger. They observed that the helical coils are efficient for low Re. Also the ratio of tube diameter to coil diameter should be large enough for large intensities of secondary flows inside the tubes. (J.S Jaya kumar, et. al, 2008) carried out an experimental study of fluid to fluid heat transfer though a helical coiled tube. Heat transfer characteristics were also studied using CFD code fluent. They observed CFD predictions match reasonably with experimental results for all operating conditions. The heat transfer studies of a helical coil immersed in a water bath was studied by (Prabhanjan, et al, 2004). (Ivaan Di Piazza, et al, 2010) obtained computational results for turbulent flow and heat transfer through curved pipes. Nusselt number and pressure drop were calculated by using different turbulent models. Out of those RSM-ω gave better results when compared to the other models in the prediction of nusselt number and heat transfer.

In the present paper a helical coil heat exchanger was modeled and simulated using computational fluid domain for cooling hot water by applying fixed wall temperature boundary conditions. Heat transfer parameters like

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temperature drop, heat transfer rate heat transfer coefficient, nusselt number and pressure drop were calculated. Simulation results were compared with the analytical results using the correlations developed by different researchers. Also the simulation results of the helical coil were compared with the results obtained for a straight heat exchanger of equal length and similar operating conditions in order to compare its performance related to heat transfer characteristics.

Geometry and parameters of helical coil

The major geometric dimensions include the diameter of the tube(d), curvature diameter or pitch circle diameter of the coil (D) and coil pitch (increase of height per rotation, p). Table 1 shows dimensional and operating parameters used in the present study.

Table 1 Dimensional & operating parameters of the helical coil heat exchanger

S.No	Dimensional parameters	Dimension
1	Average coil diameter	40 mm
2	Tube diameter	10 mm
3	Tube length	1000 mm
4	Working fluid	Water
5	Average hot water temperature	332K
6	Constant wall temperature	293K

For analytical calculations of heat transfer through the helical coil the following equations and correlations developed by different researchers have been used.

1. Mean velocity of flow through the coil $u = \frac{m}{\rho A}$ (1)
2. Reynolds number $Re = \frac{\rho u d}{\mu}$ (2)
3. Dean number $De = Re \times \left(\frac{d}{D}\right)^{0.5}$ (3)
4. $Nu = 3.313.31\, De^{0.115}\, Pr^{0.0108}$ for 8>De>1200 (Kalb, C. E, et al 1972) (4)
5. $Nu = 0.023 Re^{0.85}\, Pr^{0.4} \delta^{0.1}$ for Re > 2000 (Roger, et al, 1964) (5)
6. $h_i = \frac{Nu \times k}{d}$ (6)

Numerical simulation

Numerical solution is being carried out with steady state implicit pressure based solver using Fluent code (2011). The governing partial differential equations for mass and momentum are solved for steady state flows. Pressure velocity coupling is carried out using the PISO algorithm. Discretisation is done using second order upwind scheme.
Mean Flow Equations:
All the equations are presented in Cartesian tensor notation.

$$\frac{\partial}{\partial x_i}(\rho U_i) = 0$$

Continuity:

Momentum equation:

$$\frac{\partial}{\partial x_j}(\rho U_i U_j) = \frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) - \rho\overline{u_i u_j}\right]$$

Energy equation:

$$\frac{\partial}{\partial x_j}(\rho U_i T) = \frac{\partial}{\partial x_j}\left[\frac{\mu}{\Pr}\frac{\partial T}{\partial x_j} - \rho\overline{u_i t}\right]$$

Numerical scheme

The geometric model of the straight tube and helical coil were constructed using work bench in ANSYS 14 environment. In order to numerically establish the effectiveness of helical coil heat exchanger the tube diameter and length of the coil were assumed to be same that of straight tube. Pitch circle diameter was considered to be 40 mm. The three dimensional computational domain modeled using hex mesh for both models are as shown in fig 1. The complete domain of straight tube consists of 28,028 elements and helical tube consists of 42602 Elements. Grid independence test was performed to check the validity of the quality of the mesh on the solution. Further refinement did not change the result by more than 0.9% which is taken as the appropriate mesh quality for computation. Constant wall temperature boundary condition was imposed on the wall of the tube. Fluid is made to cool down as it flows along the tube by specifying a wall temperature of 293 K. At the outlet, a pressure outlet boundary is enforced. Conservation equations were solved for the control volume to yield the velocity and temperature fields for the water flow in the coil. Convergence was affected when all the residuals fell below 10^{-6} in the computational domain.

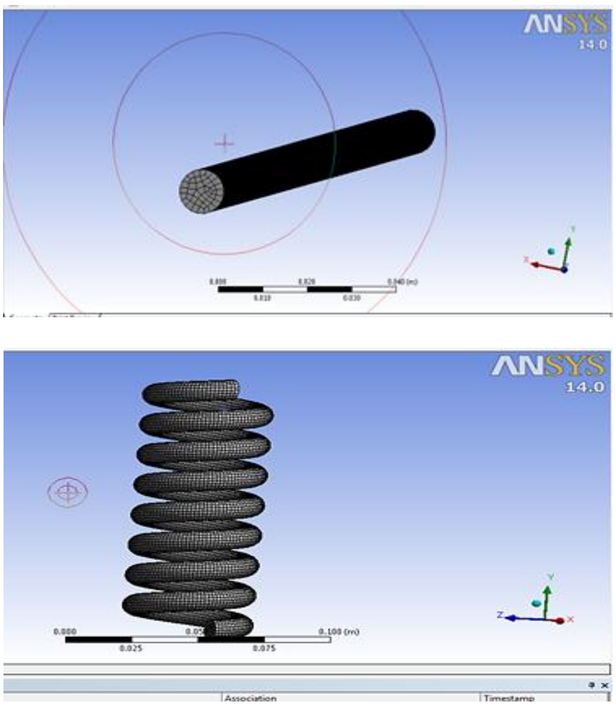

Fig1. Meshed model of straight tube and helical coiled heat exchanger

Results and discussions

CFD computations were done for three different mass flow rate of water 0.005, 0.02 and 0.05 kg/s respectively for both straight and helical coiled tube. Reynolds number corresponding to these mass flow rates were 1068, 4274 and 10685 respectively. Performance parameters adopted for comparison are outlet temperature of water, heat transfer rate, heat transfer coefficient, nusselt number and pressure drop in both the cases. Figure 2 shows the path line plot for helical coil. In the helical coil as the fluid flows through the coil, fluid particles undergo rotational motion. The fluid particles also undergo movement from inner side of the coil to the outer side and vice versa. It can be noted that these fluid particles are taking various trajectories and also move with different velocities. The particles, which were forming a line to begin with, are found to be totally scattered at the pipe exit, where as in the case of straight tube the fluctuations are not that severe. This causes fluctuations in the values of Nusselt number and hat transfer coefficient inside the helical coil.
In order to validate the CFD results the important parameters like Nu and heat transfer coefficient were calculated by using the different correlations both for straight and the helical coiled tube. Figures 3 and 4 show the CFD simulated nusselt number plot vs correlation values for straight and helical tubes for the different mass flow rates. The results have shown a good agreement between the correlation values used by different researchers and fluent results as the average error is within 3% and 4.5% for both cases. Similarly figures 5 and 6 shows the plot of heat transfer coefficients for both cases. The average error is 2% for straight tube and 5% for coiled tubes. Slightly higher error for the helical coil may be attributed due to the uneven movement of fluid particles in the curvature path as discussed in the previous section.

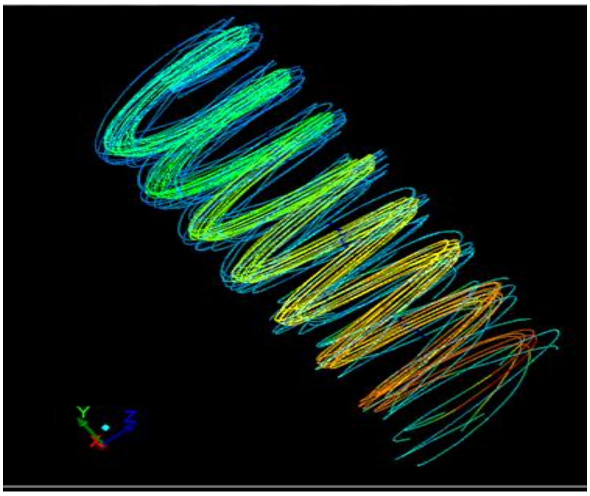

Fig 2. Path line plot for the helical coiled tube

Figure 7 show temperature distribution plot of the fluid along the helical path for a mass flow rate of 0.02 kg/s. Figure 8 shows the variation of drop in water outlet temperatures with the mass flow rates. It can be seen that temperature drop for helical coiled tube is higher than the straight tube. This is due to the curvature effect of the helical coil. Fluid streams in the outer layer of the pipe moves faster than the fluid streams in the inner layer. This difference in the velocity will set in a secondary flow by which heat transfer will be increased. It can be seen that for the helical coil the average temperature drop was increased by 9.5% as compared to the straight coil when the mass flow rate varied from 0.005 kg/s to 0.05 kg/s. As the mass flow rate increases the temperature drop decreases in both cases. At higher mass flow rates due to the increased velocity resident time for the fluid decreases thus reducing the temperature drop. The difference in temperature drops between straight and helical coil increases with the mass flow rate as depicted by fig 8 showing the better performance of the helical coil. This may be due to the increased turbulence and secondary flows at higher mass flow rates in the helical coils than the straight tube.

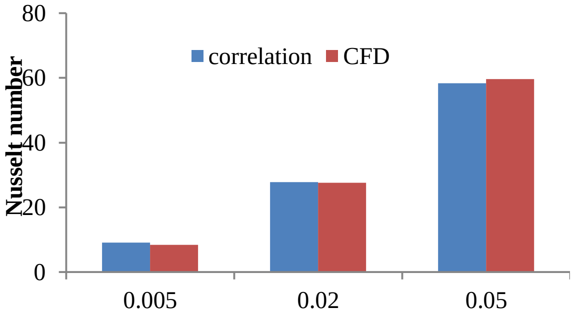

Fig 3. Comparison of correlation and CFD values of Nusselt number for straight tube

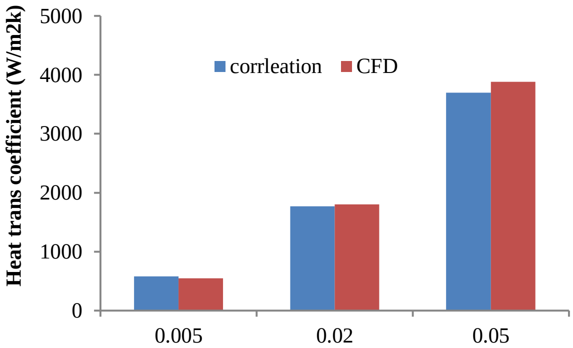

Fig 5. Comparision of correlation and CFD values of heat transfder coefficient for straight tube

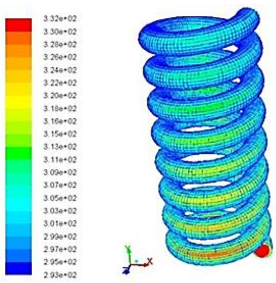

Fig 7. Temperature distribution for the helical coiled tube for mass flow rate of 0.02 kg/s

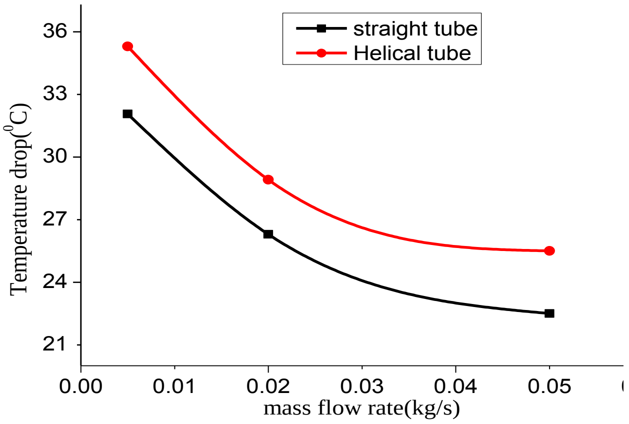

Fig 8 .Variation of temperature drop with mass flow rate for straight and helical tube

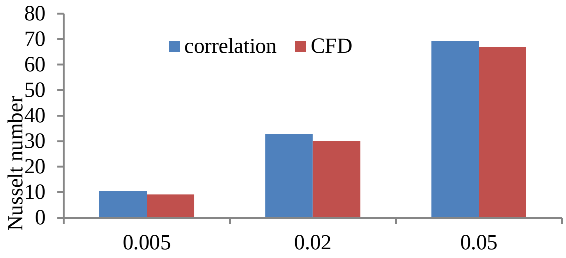

Fig 4. Comparision of correlation and CFD values of Nusselt number for helical tube

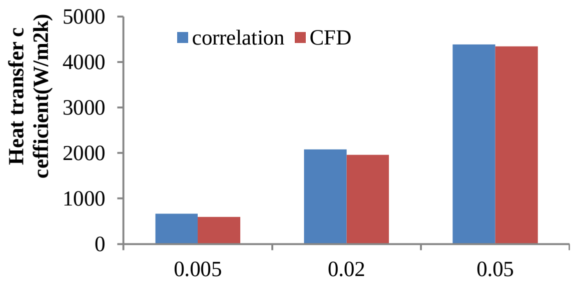

Fig 6. Comparision of correlation and CFD values of heat transfer coefficient for helical tube

Figure 9 shows the variation of heat transfer rate through the water for straight and helical coil with mass flow rate. Heat transfer rate increases with mass flow rate for both cases, in the second case being higher than the initial showing the improvement in heat transfer through helical coils. On an average heat transfer rate for the helical coil increases by 11% when the mass flow rate was increased from 0.005 to 0.05. It can be observed that for higher mass flow rate, heat transfer increases but the temperature drop decreases. This may be attributed due to the less repository time available for water.

Figure 10 show the variation of nusselt number for straight and helical coils. Nusselt numbers corresponding to the helical coils are higher than the straight tube for all mass flow rates. This is because of the secondary flow in the helical coils which aid the heat transfer. For low mass flow rates there was not significant increase in Nu whereas for higher mass flow rates under similar conditions significant change was noticed. On an average nusselt number increased by 10% when the mass flow rate was changed from 0.005 kg/s to 0.05 kg/s. In the helical coils at higher mass flow rates Reynolds number increases and also fluid turbulence increases. Higher turbulence increases the intensity of secondary flow and hence the nusselt number.

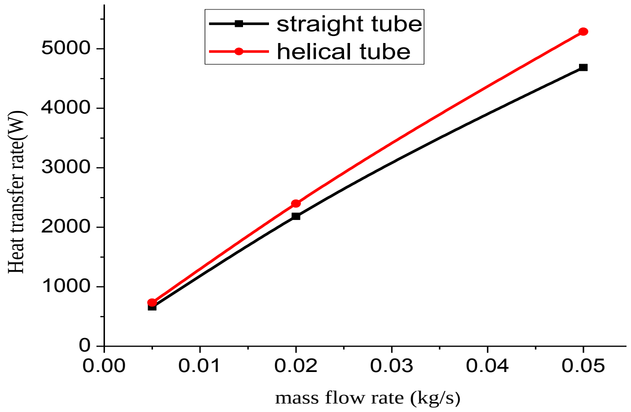

Fig 9 .Variation of heat transfer rate with mass flow rate for straight and helical tube

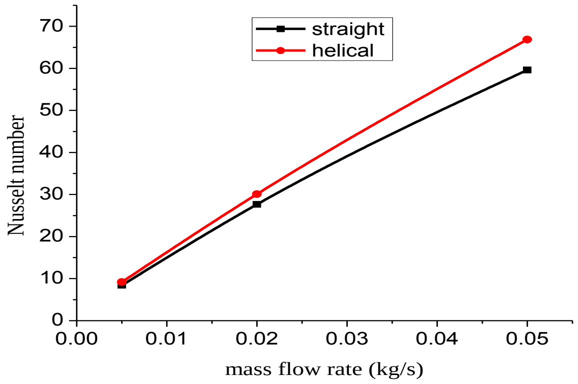

Fig 10 .Variation of nusselt number with mass flow rate for straight and helical tube

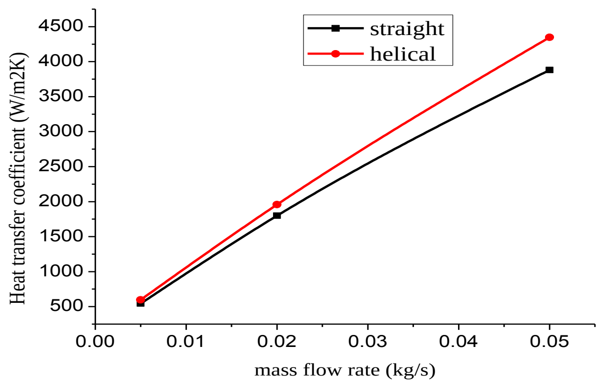

Fig 11 .Variation of heat transfer coefficient with mass flow rate for straight and helical tube

Figure 11 show the variation of heat transfer coefficient for different mass flow rates. From the graph it is revealed that as the mass flow rate increases heat transfer coefficient also increases as expected since heat transfer rate is proportional to the mass flow rate. Further for helical coils heat transfer coefficient has increased by 8.5% when the mass flow rate is increased from 0.005 to 0.05 kg/s. The same explanation described above as for Figs. 6 and 7 can be given.

Figure 12 show the variation of pressure drop over the entire length of the helical coil and Figure 13 show the comparison of pressure drops for the straight and helical coils. Pressure drop for the helical coils is found to be more than the straight tube for all mass flow rates. Due to centrifugal forces the pressure drop in coil pipes is higher than pressure drop in the same length of straight pipes. Presence of secondary flow dissipates kinetic energy, thus increasing the resistance to flow. For lower mass flow rates pressure drop varies linearly whereas on increasing the mass flow rate pressure drop varies exponentially as seen in the graph.

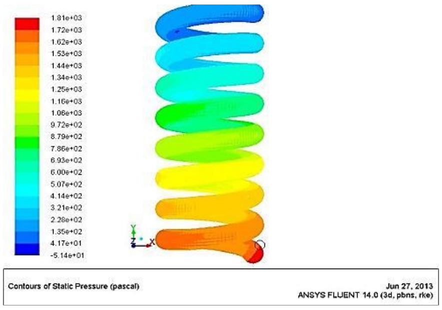

Fig 12. Pressure drop along the length of the helical coiled tube

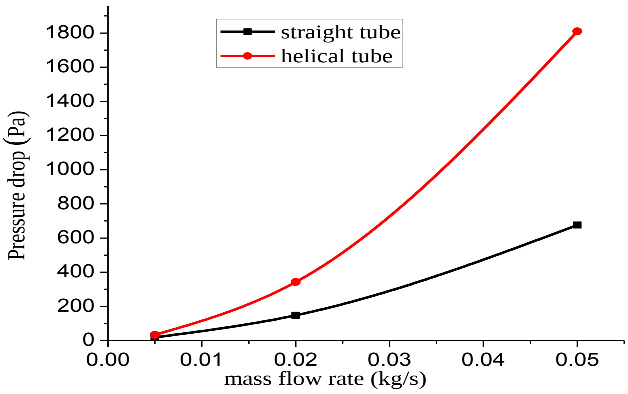

Fig 13.Variation of pressure drop with mass

Conclusions

In the present work CFD analysis for a helical coil tubular heat exchanger was carried out and the results of heat transfer parameters have been compared with the straight coil under similar geometrical and operating conditions. CFD results are validated by the correlations used by the different researchers. There was a close agreement between the CFD predicted and correlation results. Simulation results indicated that heat transfer rate, nusselt number and heat transfer coefficient are higher in case of helical coils when compared with the straight tube. Pressure drop for helical coil is found to be more when compared with the straight tube for identical conditions. For higher mass flow rates it varies exponentially indicating the necessity of higher pumping power in case of helical coils.

Nomenclature

u Mean velocity of flow (m/s)
Re Reynolds number
P density of fluid (kg/m^3)
d Tube diameter(m)
D pitch circle diameter(m)
Pr Prandtl number
δ Curvature ratio
µ Coefficient of dynamic v viscosity
k Thermal conductivity(w/mK)
Nu Nusselt number

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